Optical Sensing in Engines: Recent Progress and Future Goals

Engine Research Center
Mechanical Engineering Department
University of Wisconsin – Madison

Professor Scott T. Sanders

Students: Laura A. Kranendonk, Christopher L. Hagen, Andrew W. Caswell, Chun Lan, Renata J. Bartula, Thilo Kraetschmer

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Outline:

- Overview of optical diagnostics (see also ERC webpage: www.erc.wisc.edu)
- *Spectral* engine analysis in the ERC
- Hyperspectral: what and why?
- Engine data: findings and future plans

Optical Diagnostics in Engines: Research Landscape

- Optical diagnostics have played a key role in engine research for decades
- More than 10 years ago: many new diagnostic development efforts (among engine manufacturers, national laboratories, universities, small businesses, …)
- In the last ~ 10 years:
  - reduced development of new diagnostics
  - emphasis on refining, applying proven diagnostics
- Today: many parties comfortable with standard diagnostics
  - high speed visualization
  - thermal emission / chemiluminescence spectroscopy
  - particle imaging velocimetry
  - laser Doppler anemometry
  - phase Doppler particle anemometry
  - Schlieren/shadowgraph imaging
  - laser induced fluorescence

but there is less development effort

Comparison with Medical, Military Applications

- Increased optical developments in medical, military applications
- Example: at the May 2006 Conference on Lasers and Electro Optics (CLEO), ~ 20 new laser designs for medical applications were announced; at most 2 presenters even mentioned combustion as a possible application
- Larger funding in these markets has been attracting many researchers away from combustion

- However, as we know, combustion / engine / mobility / energy research is an important area
- *New* optical diagnostics can continue to play a very important role

Diagnostics wish list: What would we like to measure?

- Composition of the gas phase (N species)
- Gas temperature
- Velocity (3 components)

- Also: composition and morphology of the solid phase (soot), etc.

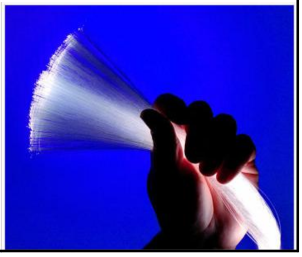
- Goal: measure the above for all times and all points in space
- One application: compare with computational results, improve predictive capabilities

All times and all points in space in an engine

- To resolve most phenomena of interest, we need
  - Spatial resolution ~ 30 μm
  - Time resolution ~ 10 μs

- 30 μm spatial resolution → 10^{12} data points in the engine
- 10^{12} data points every 10 μs → 10^{17} data points per second

- Imagine we wish to measure just one value (temperature) with 8-bit precision at this rate → 10^{18} bits/s: this is *about 10x the cumulative data flow for the entire planet!*
- Could transmit this data through the fibers shown here: but it would be too much to process



Additional challenges

- That was only temperature, other parameters are desired
- The engine produces work, not temperature signals. To extract one accurate temperature at a single point, one could use coherent anti-Stokes Raman spectroscopy (CARS), for example. However:
  - ~ 500 *spectral* data points are required to infer the one parameter of interest, temperature
  - The CARS setup is challenging.
  - The 'point' may be larger than 30 μm.

Sprays: one example of even more challenges

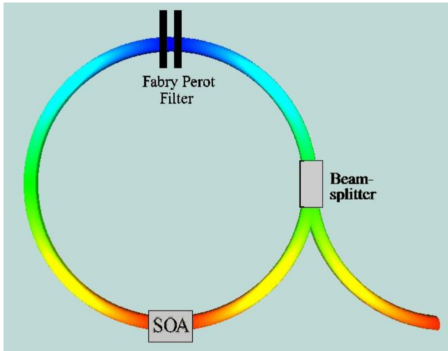
- In a spray one may desire 30 μm → 300 nm, 10 μs → 300 ns
- It is clear that we cannot achieve the true goals.
- How should we proceed with optical diagnostics in engines?

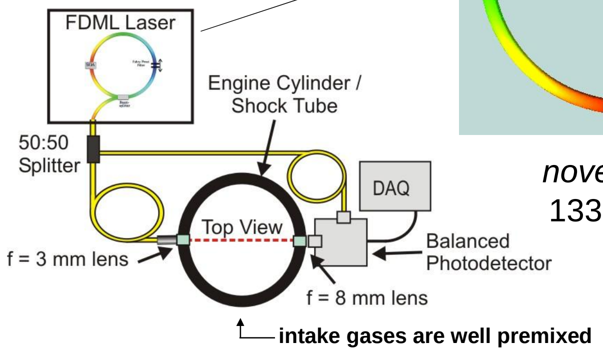
The present

- Continue to make measurements of interesting phenomena at integral length scales
- Combine diagnostics to
  - Overcome limitations
  - Provide a more complete picture of the process
  - Tie results directly to combustion phenomena

Combining Diagnostics to Overcome Limitations

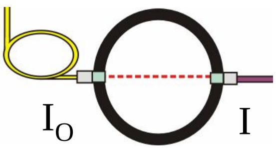
Setup for temperature measurements





novel, custom laser, scans 1330-1380 nm every 5 μs

Combining Diagnostics to Overcome Limitations

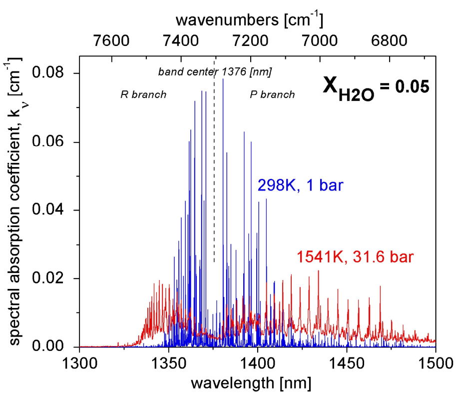


Beer's Law:

$$T_\nu \equiv \frac{I}{I_o} = \exp(-k_\nu \cdot L)$$

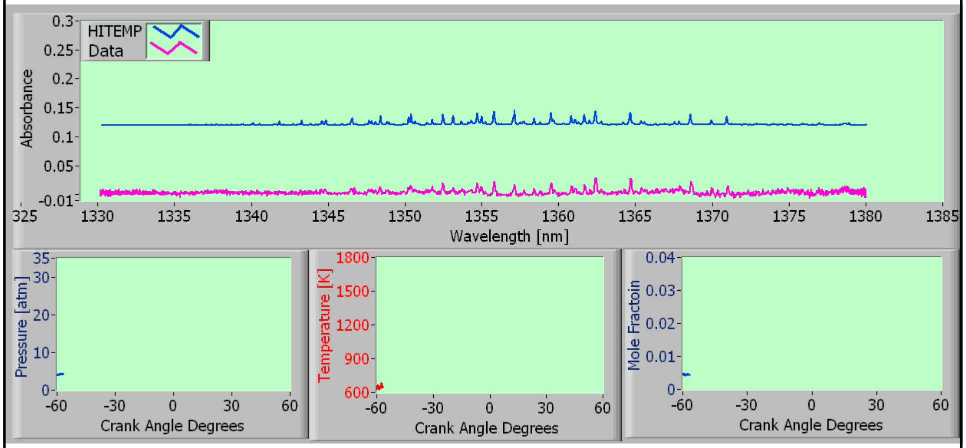
HITEMP simulation results:

Background for temperature measurements



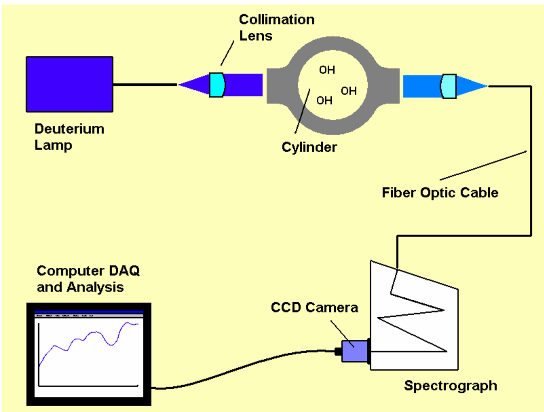
Combining Diagnostics to Overcome Limitations

Example record for one engine operating condition
(50-cycle average, temperature and mole fraction inferred from spectra)



Combining Diagnostics to Overcome Limitations

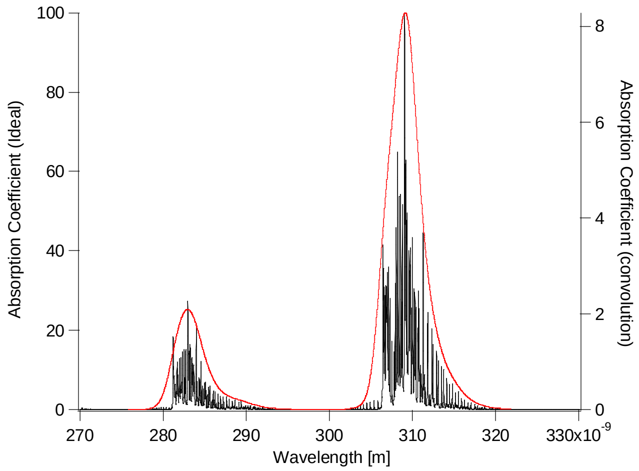
Setup for OH absorption measurements



Experiment performed under Prof. Jaal Ghandhi

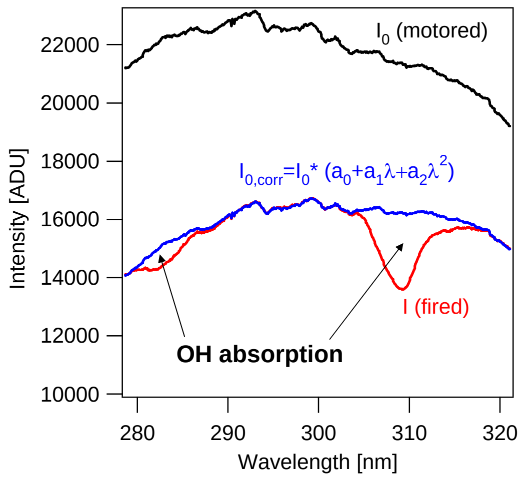
Combining Diagnostics to Overcome Limitations

Expected absorption signature



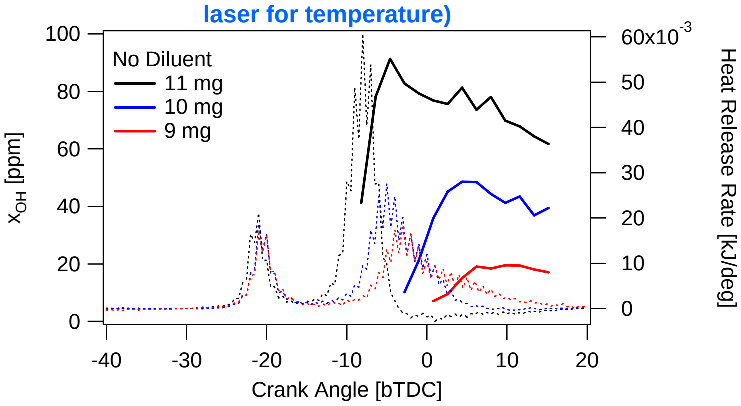
Combining Diagnostics to Overcome Limitations

Raw data recorded in the engine (UV spectrometer)



Combining Diagnostics to Overcome Limitations

Results
(UV spectrometer +
wavelength-agile
laser for temperature)



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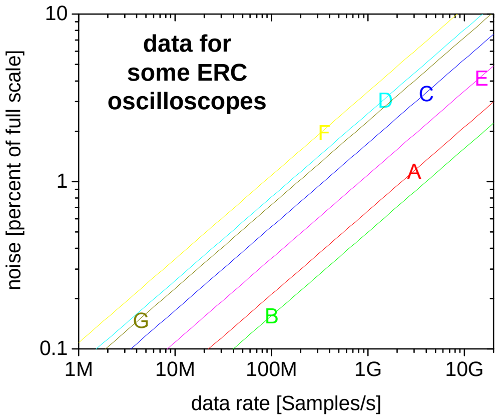
  - Tie results directly to combustion phenomena

The future

- RESOLUTION
  - Spatial
  - Temporal
  - Spectral
  - Signal to noise ratio

Tradeoffs

- RESOLUTION
  - Spatial
  - Temporal →
  - Spectral
  - Signal to noise ratio →



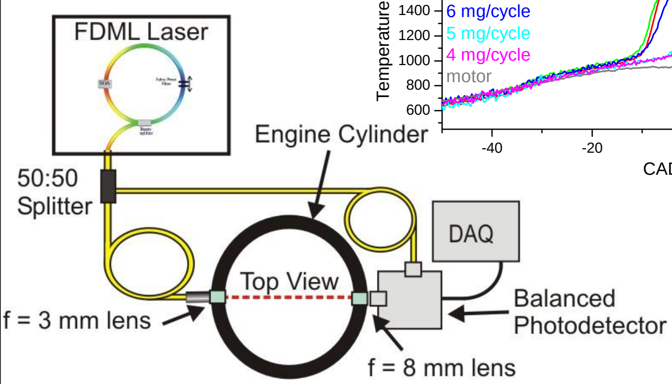
Spectral Engine Analysis

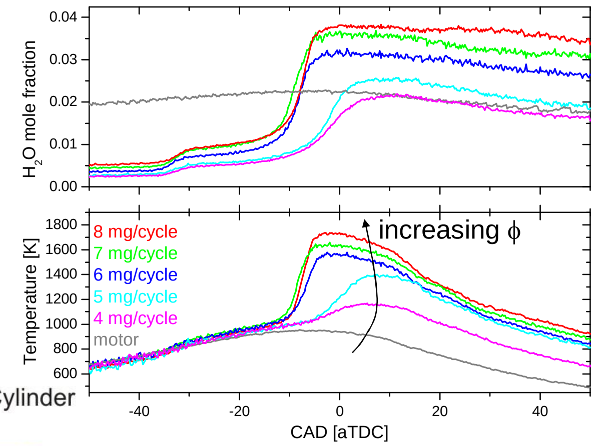
- RESOLUTION
  - Spatial
  - Temporal
  - Spectral
  - Signal to noise ratio

- Focus on spectra: different than most combustion diagnostics
- Spectra provide possibility of accurate, quantitative measurements
- Combined spatial / spectral resolution is a key future goal (example: we have designed a laser that scans 300-320 nm at arbitrary speeds for fluorescence measurements)

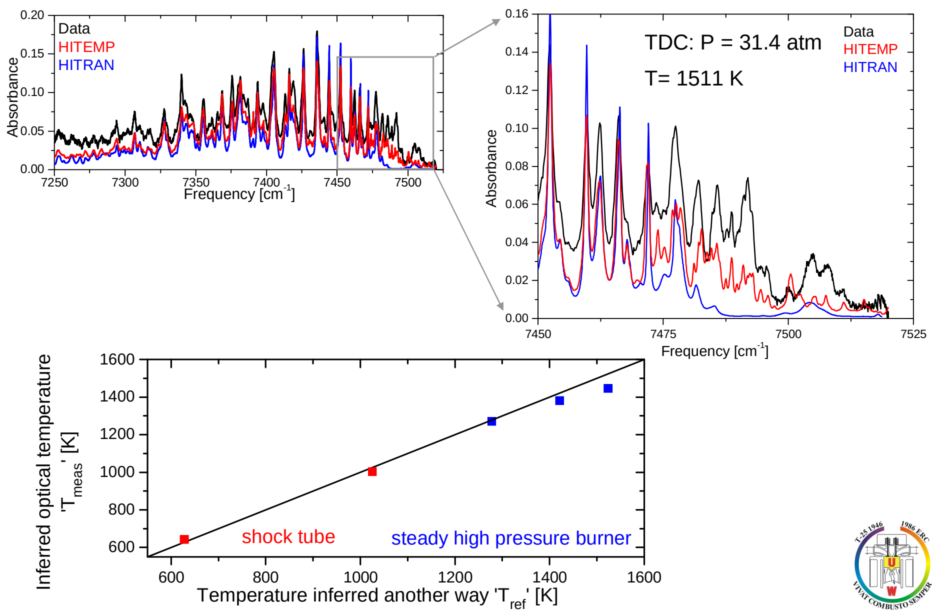
Typical experimental schematic & results

- Focus on spectra: different than many combustion diagnostics
- Path-integrated, in-cylinder measurements
- Provides species mole fractions and gas properties

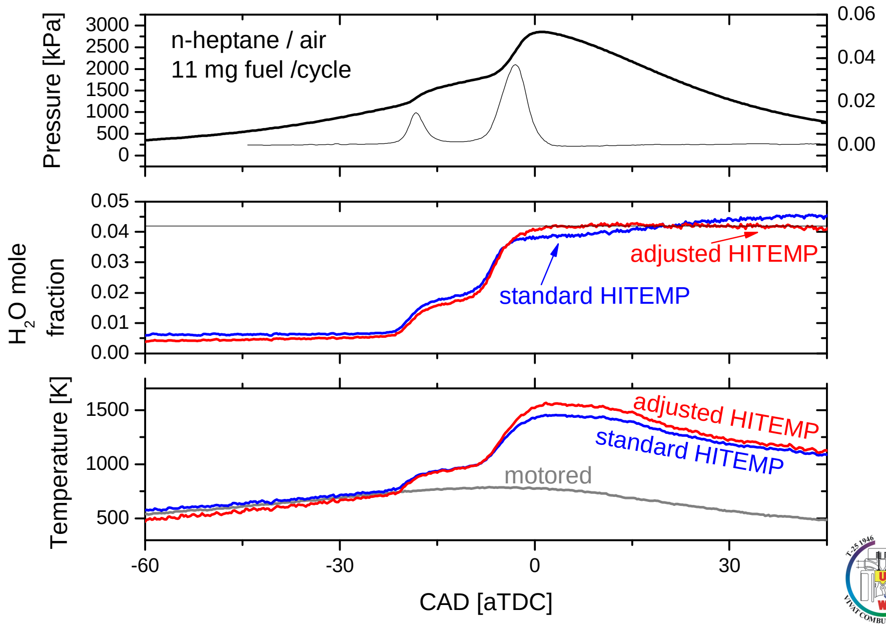




Are the temperatures accurate?



Progress using a patch to HITEMP



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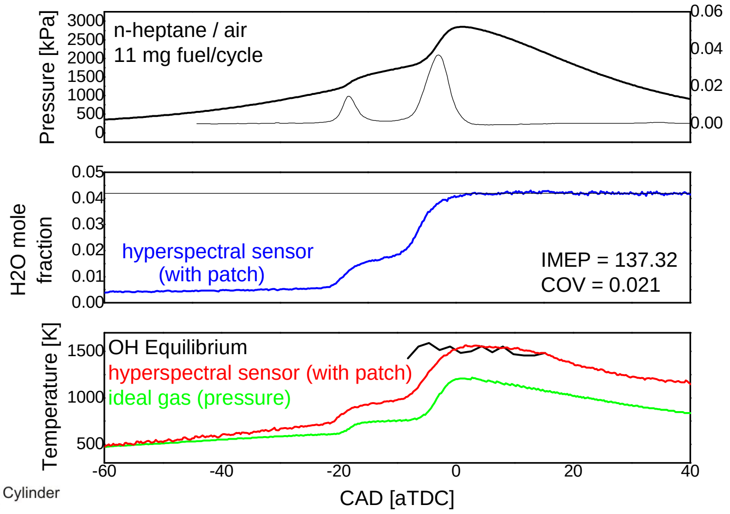
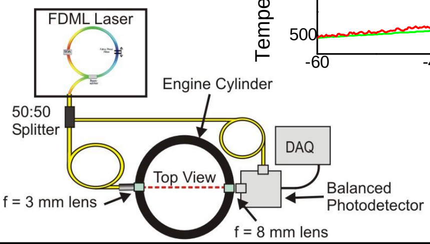
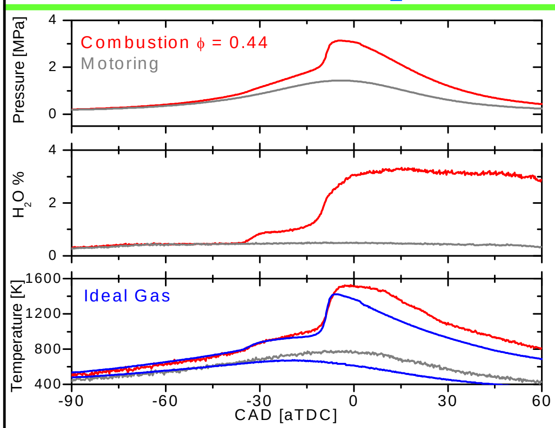
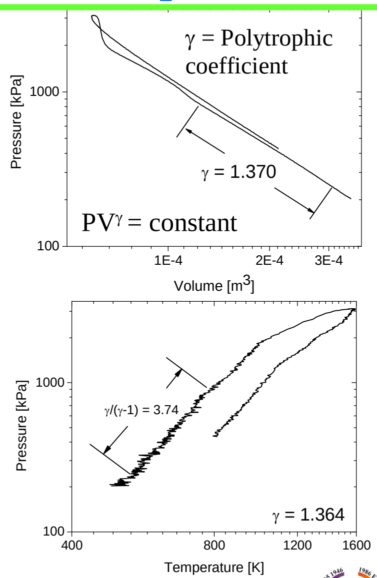


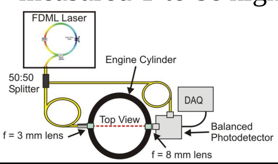


Additional experimental comparisons



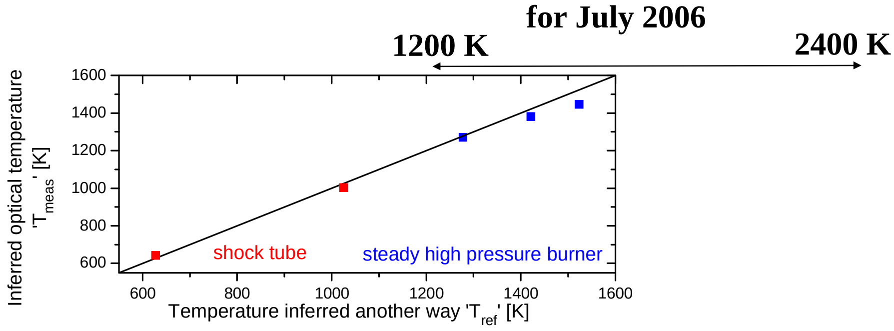


- Blow-by, thermal boundary layers cause measured T to be higher than ideal gas T



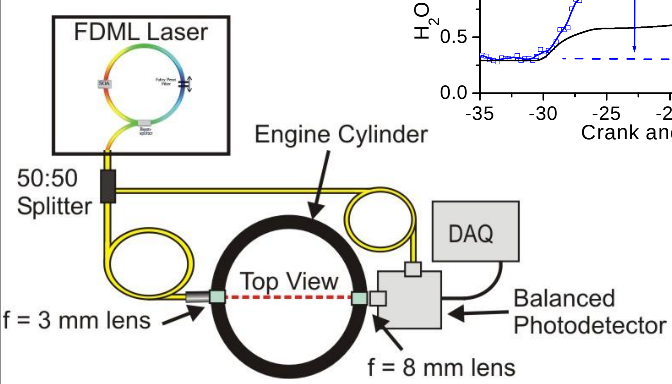
Plan for further shock tube tests

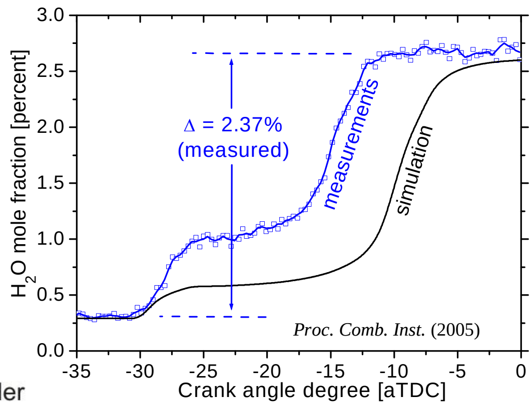
More shock tube experiments planned for July 2006



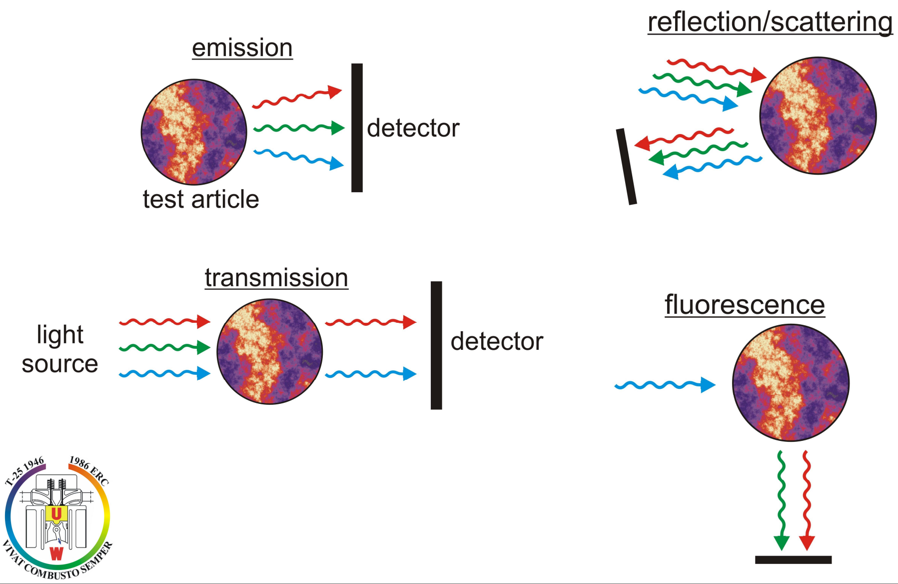
Plans for species measurements

- Focus on spectra: different than many combustion diagnostics
- Path-integrated, in-cylinder measurements
- Provides species mole fractions and gas properties





Introduction to Hyperspectral Sensing: Generic Spectroscopy Arrangements



Hyperspectral = ‘too many spectra’

MORE INFORMATION

Broad spectral coverage (> 200 cm^{-1}):

- multiple species with a single source
- ability to monitor broad spectral features (heavy or high-pressure gases, supercritical fluids, liquids, solids, etc.)
- reality checks (are you really measuring what you think you’re measuring?)

High-resolution (< 1 cm^{-1}):

- higher SNR in gas spectroscopy
- discrimination of multiple species

HIGHER INFO RATE

High-speed (> 1 spectrum every 50 μs):

- Immunity to ‘slow’ noise sources: vibration, beamsteering, etc.
- Compatibility with transient experiments (explosions, shock tubes, pulsed magnetic fields, video-rate OCT, etc.)

Why hyperspectral?

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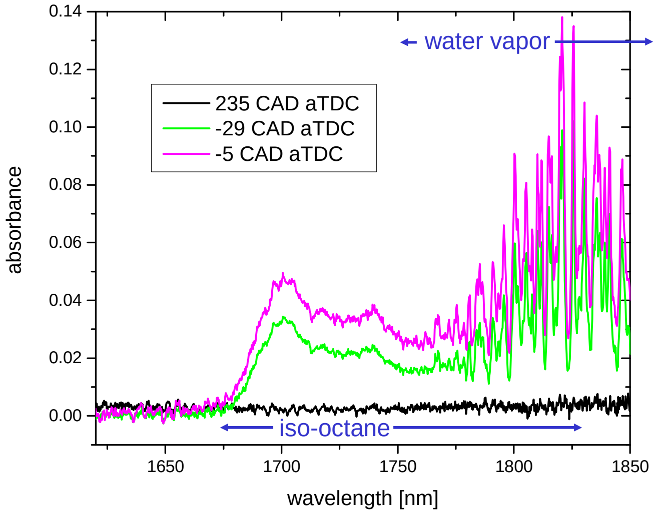

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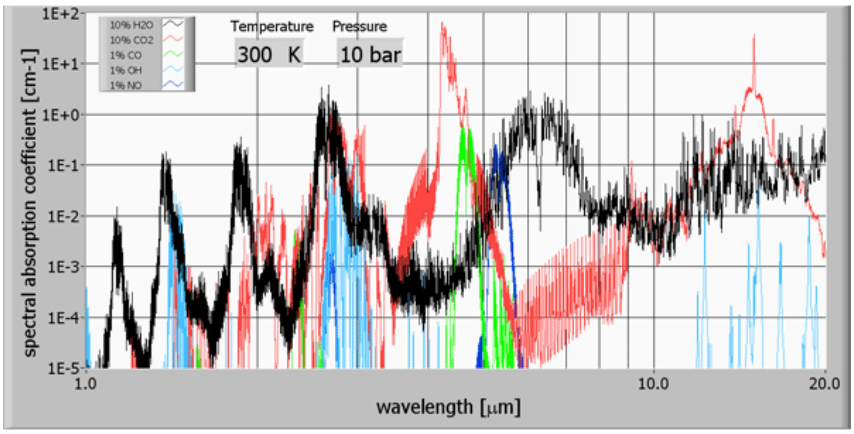

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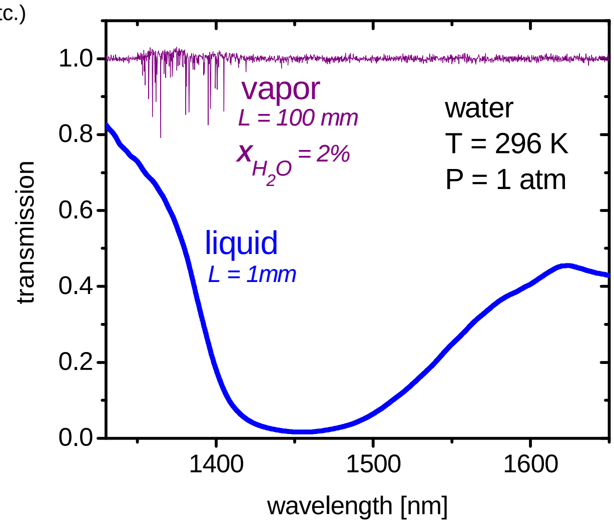

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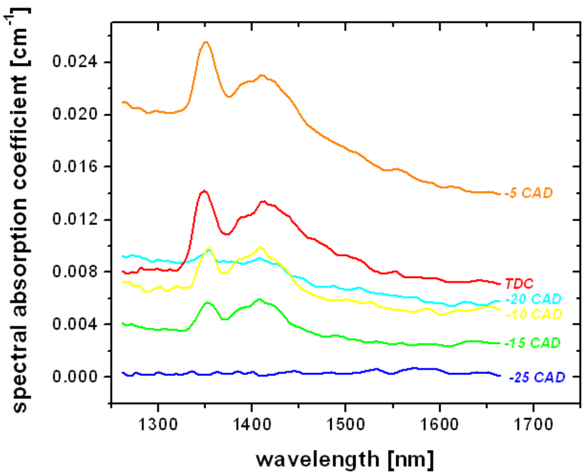

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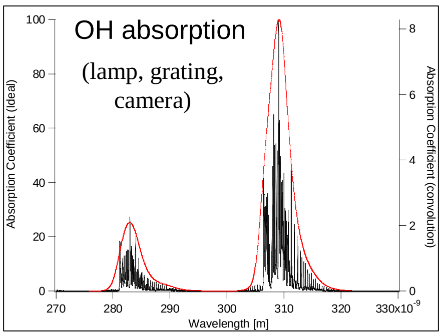

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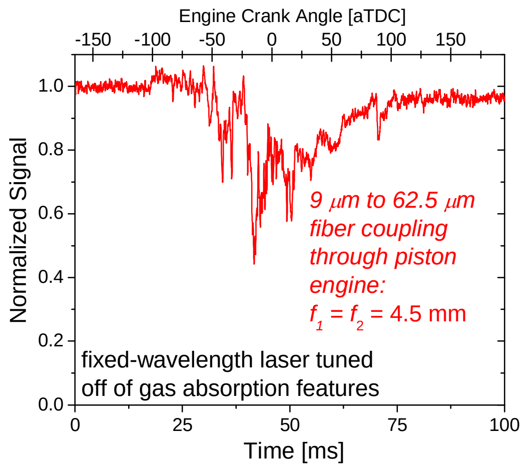

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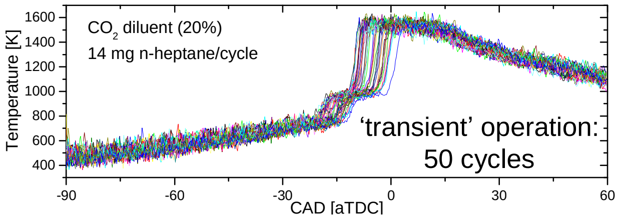
Reduced capabilities can suffice in some cases

Full hyperspectral

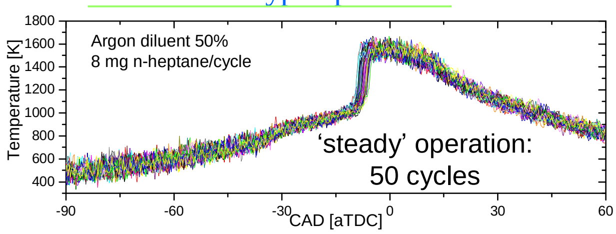
- to study transient engine behavior…



… full hyper-spectral capabilities are required.

Reduced hyperspectral

- but in a repeatable experiment, cycle-by-cycle averaging may be appropriate…

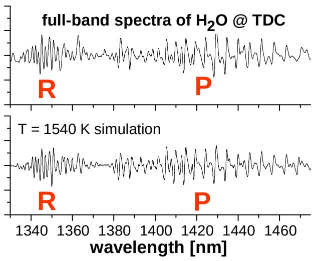


… broad, high-resolution (*but not high-speed*) sensors may suffice

Reduced capabilities can suffice in some cases

Full hyperspectral:

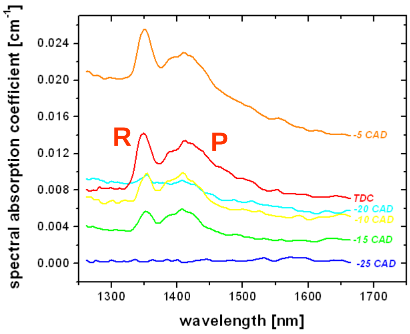
- Results from a sensor with ~ 0.2 nm resolution



'Excellent' temperature accuracy

Reduced hyperspectral:

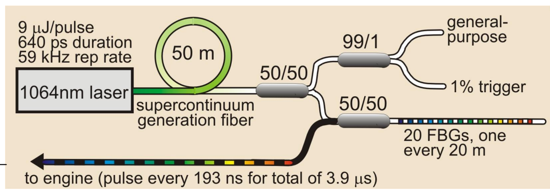
- Results from a sensor with ~ 5 nm resolution:



'Sufficient' temperature accuracy

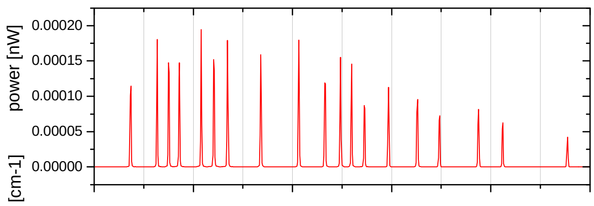
reduced DAQ requirements

Reduced capabilities can suffice in some cases

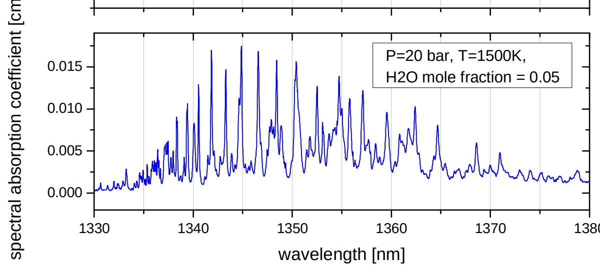


- this sensor can provide real-time engine temperatures

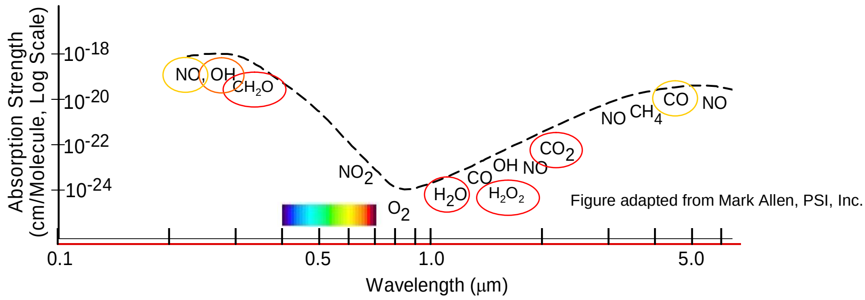
color burst as a function of wavelength:



wavelengths chosen to align with absorption features of H_2O:

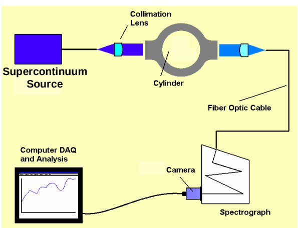


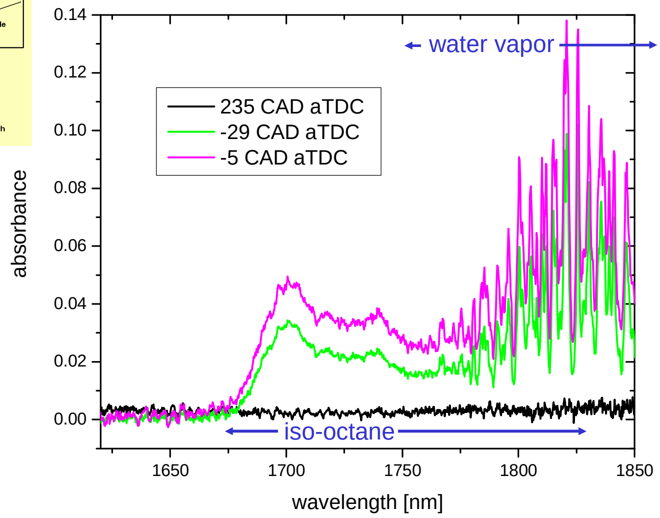
More species: extending beyond the 1 µm range



- Many important combustion species could be measured using methods similar to the ones presented here
- Shorter and longer wavelength sources need to be developed to take advantage of this technology
- Extremely broadband light could potentially measure all of the above species in one measurement.

Initial measurements in the 1800 nm range





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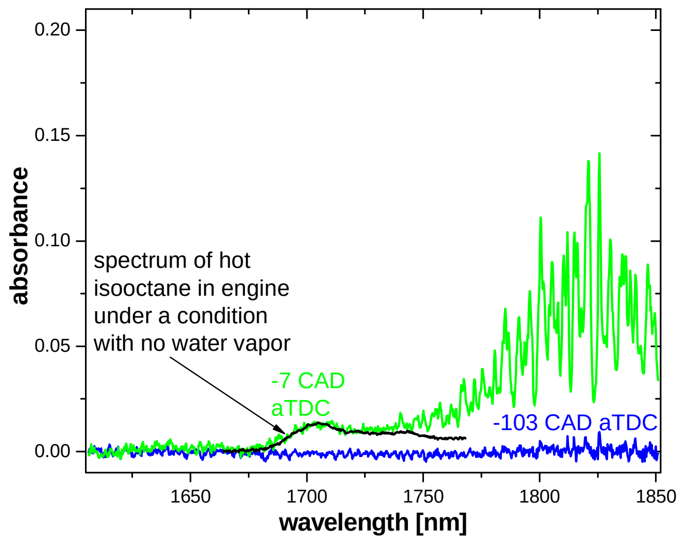

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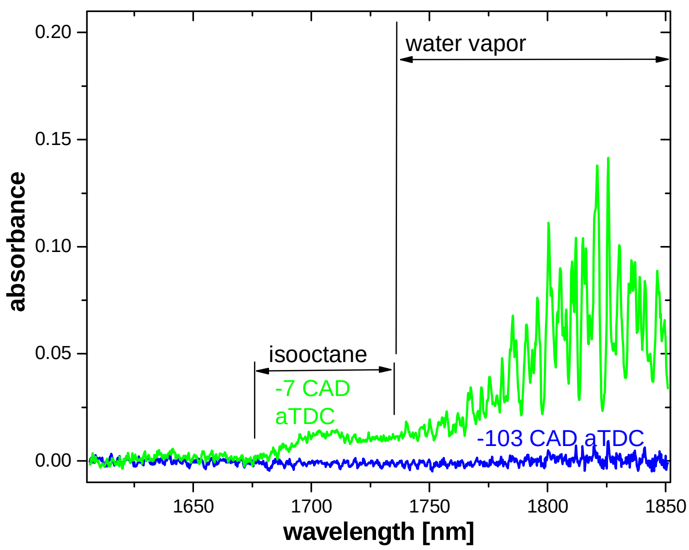

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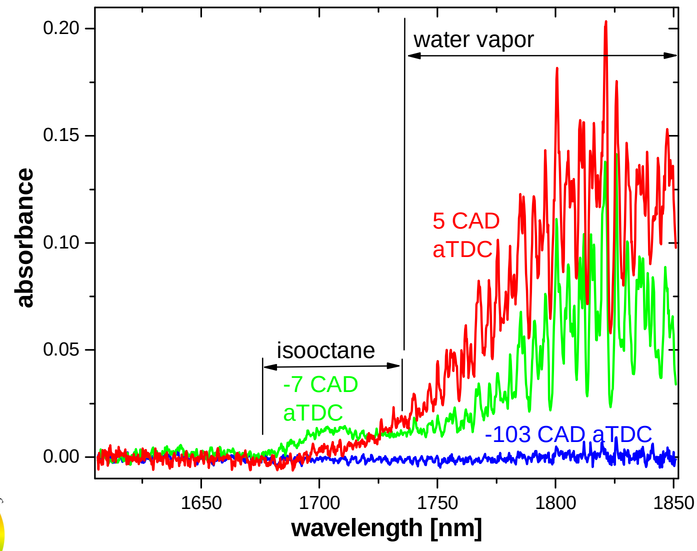

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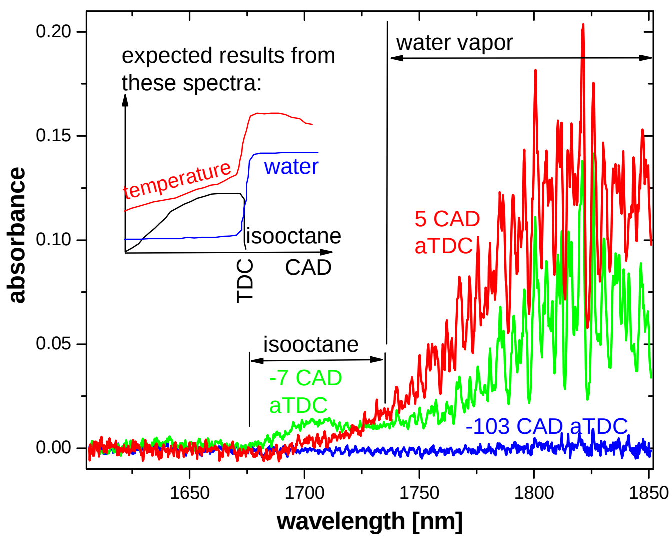
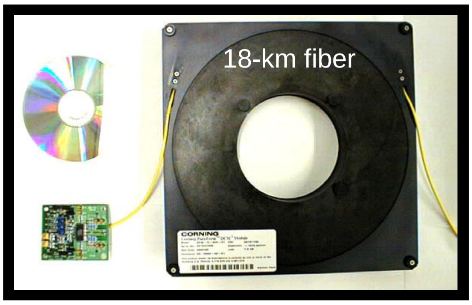


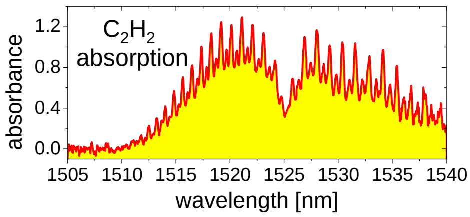
Summary

- Optical diagnostics in engines: a long history
- There is still much room for growth in this field
- Diagnostics will continue to be important to the engine community
- Spectral engine analysis is an uncommon but promising direction

Appendix A: hyperspectral source designs

Hyperspectral photonics: current research landscape





drawbacks: 4, 6, 7, 9

These sources share the following **advantages**:

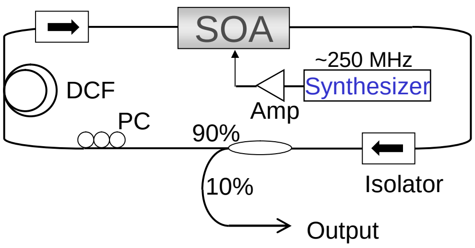
1. Inexpensive, for lasers (<$25k)
2. Wavelength = a consistent f(time)

But all suffer from one or more of the following **drawbacks**:

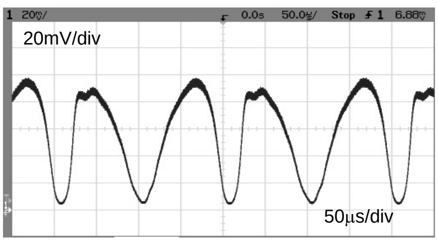
1. Moving parts
2. One scan direction superior to other
3. Unreliable at rapid sweep speeds
4. Wavelength sweeps generally too fast
5. Undesirable polarization effects
6. Unsuitable outside of telcom bands
7. Sweep rates constrained
8. Spectral resolution unstable
9. Spectral resolution = f(wavelength)

Hyperspectral photonics: current research landscape

Yamashita et. al., CLEO 2006
(University of Tokyo)



Output temporal waveform (5 kHz)



drawbacks: 2, 3, 7, 9

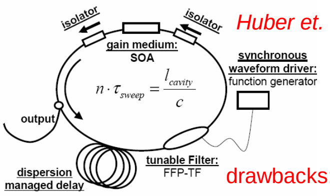
These sources share the following **advantages**:

1. Inexpensive, for lasers (<$25k)
2. Wavelength = a consistent f(time)

But all suffer from one or more of the following **drawbacks**:

1. Moving parts
2. One scan direction superior to other
3. Unreliable at rapid sweep speeds
4. Wavelength sweeps generally too fast
5. Undesirable polarization effects
6. Unsuitable outside of telcom bands
7. Sweep rates constrained
8. Spectral resolution unstable
9. Spectral resolution = f(wavelength)

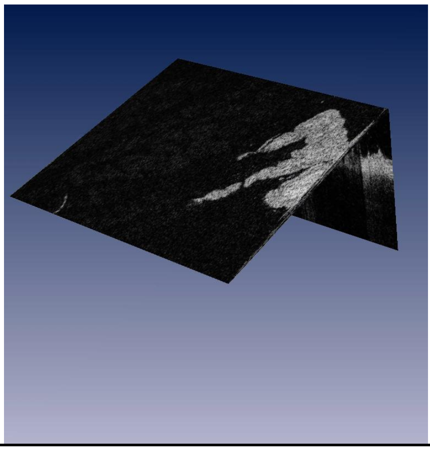
Hyperspectral photonics: current research landscape



Huber et. al., CLEO 2006

(Massachusetts Institute of Technology)

drawbacks: 1, 2, 5, 6, 7, 8



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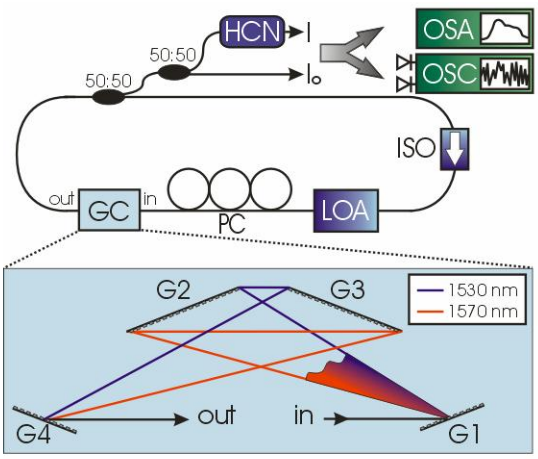
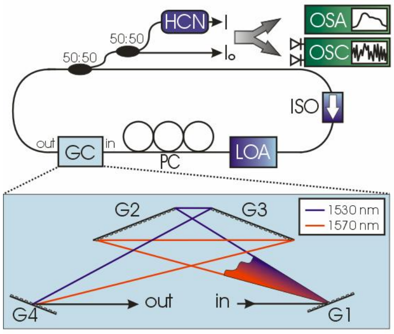
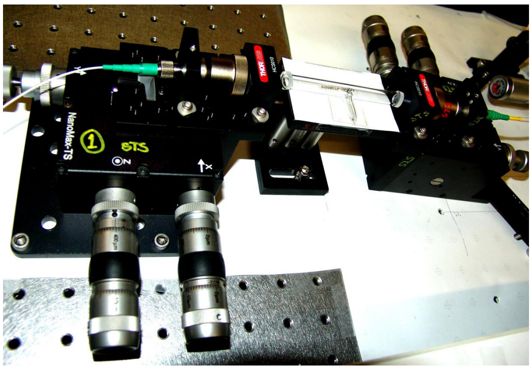
Fourier laser: in principle, no drawbacks!



- Alternative to swept wavelength source: all colors always on, each modulated at a unique frequency ('Fourier source')

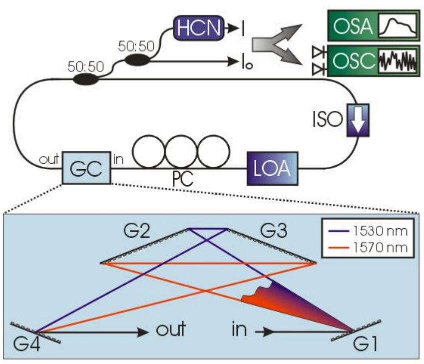
Fourier laser: in principle, no drawbacks!

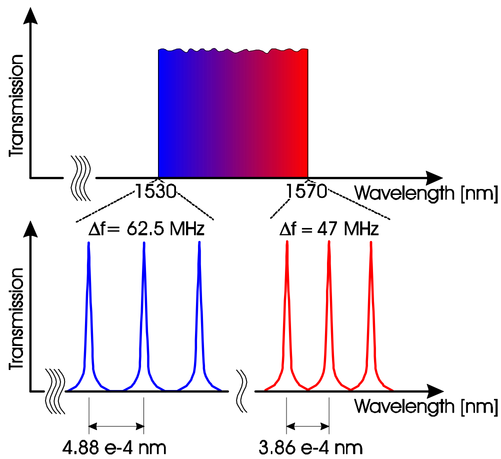




◆ Hydrogen cyanide (HCN) used as test absorber: simple spectrum near 1550 nm

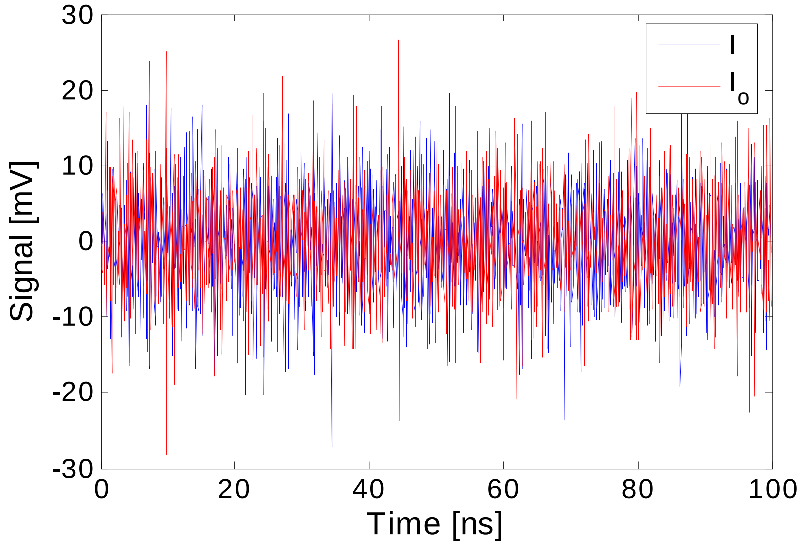
Fourier laser: in principle, no drawbacks!





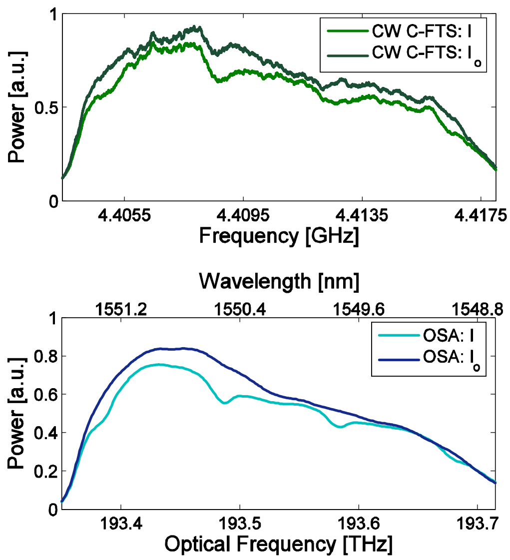
◆ Laser modes arranged so that the natural beating converts native optical frequencies to measurable frequencies
◆ Called "CW comb Fourier transform spectroscopy" (CW cFTS)

Raw time trace from a Fourier laser



- not as useless as it looks!

Reduced data



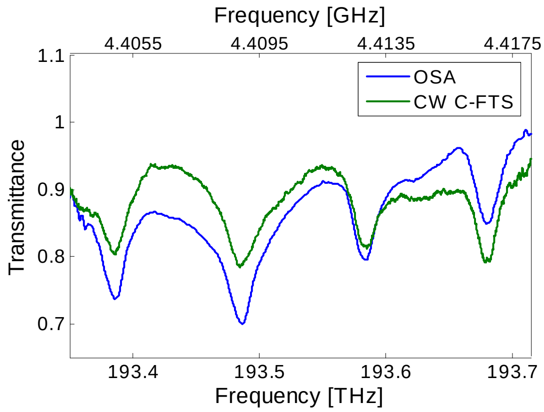
fast Fourier transform

of time traces…

… agree with

spectrometer data

Comparison of spectra



Optical Spectrum Analyzer:

Measurement Time: 750 ms

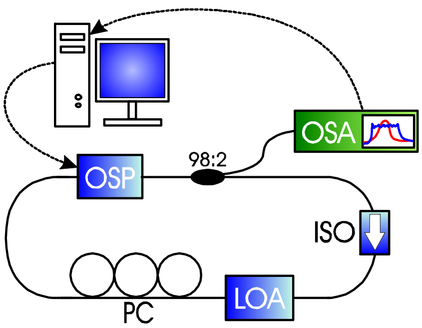
Spectral Resolution: 0.06 nm

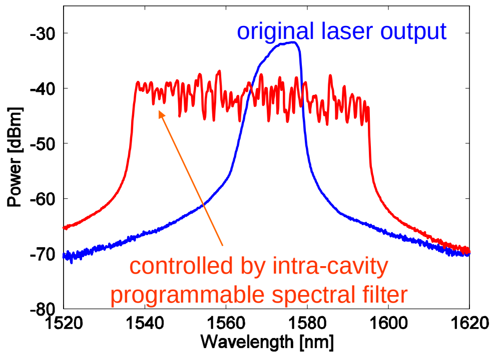
CW c FTS:

Measurement Time: 1 ms, will be reduced with improved source design

- absorption features due to HCN
- require broader spectral coverage ~ 50 nm for H_2O measurements

Spectral coverage increased using intra-cavity spectral filter





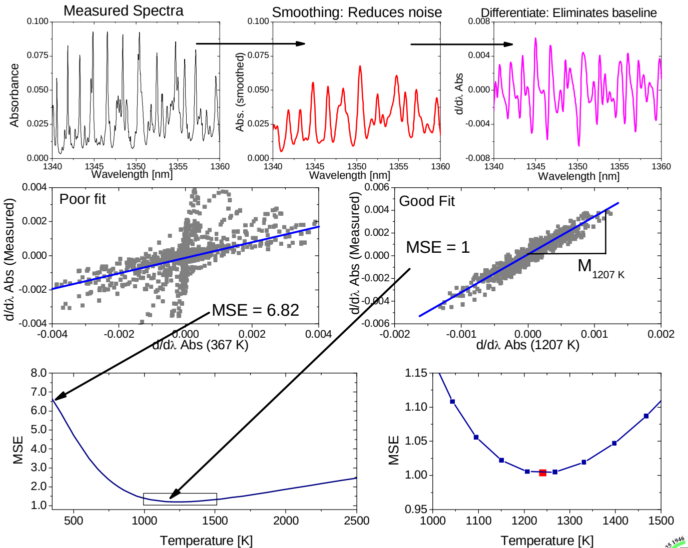
- plan to shift this sensor to 1350 nm range, apply in engines by December 2006
- based on this concept, we have also designed (proposals in review):
  - 1W source covering 300…320 nm for point measurements of [OH], [CH_2O], T by laser induced fluorescence
  - 100 mW source covering 300…2000 nm for hyperspectral transient analysis by absorption spectroscopy

Appendix B: extras

Temperature Calculations from Spectra

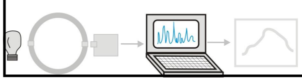
Absorbance =

$$k_\lambda L = -\ln\left(\frac{I}{I_o}\right)$$



Pressure from transducer is used to pick spectra from database (HITEMP)

Mean squared error = MSE



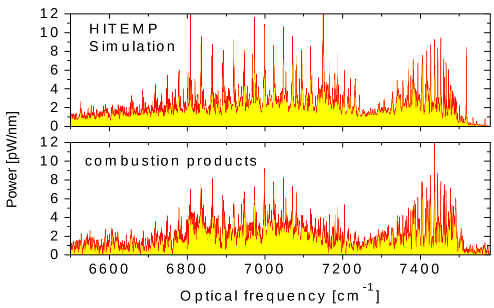
Emission Spectroscopy Example: Gas Turbine Combustor Test Rig

What is the best instrument for simply monitoring the spectrum of the emitted light?

Commercial instruments for emission monitoring

FTIR: (Thermo Electron)

OSA: (Agilent)

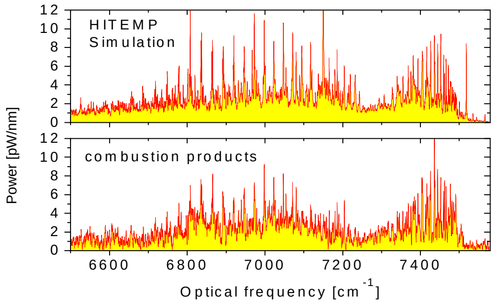


Drawbacks associated with moving parts:

- expensive (> 20k)
- slow (~ 1 s per spectrum)
- rugged?

Commercial instruments for emission monitoring

OSA: (Agilent)



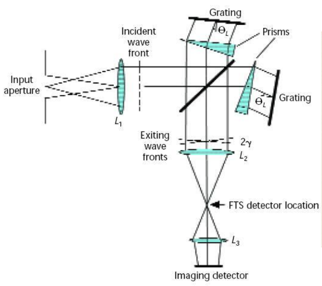
Even without moving parts, still drawbacks:

- grating spectrometers: low resolution, low throughput, or large

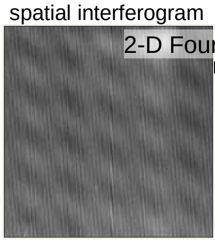
An attractive emission spectrometer: SHS

(spatial heterodyne spectrometer)

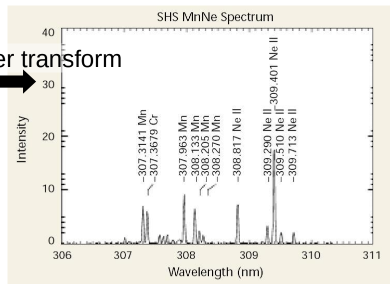
Harlander et. al., Optics and Photonics News, Jan 2004

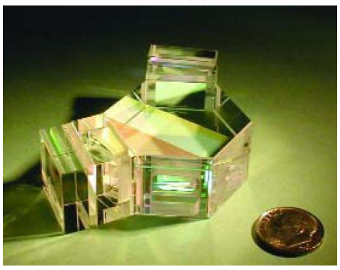


spatial interferogram



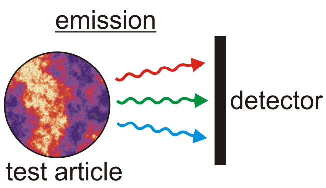
2-D Fourier transform

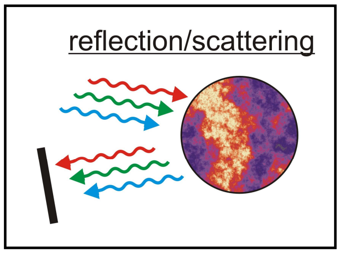


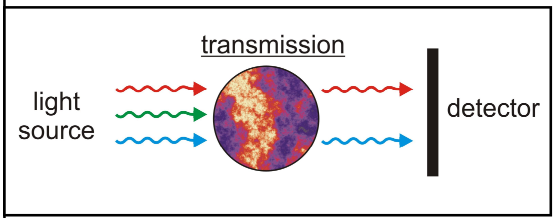


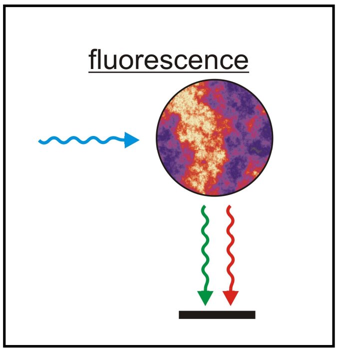
- grating-based FTS: no moving parts!
- offer broad coverage, >> 306-311 nm, maintaining spectral resolution << 1 cm^{-1}
- Prof. Sanders' opinion: about the best option for high-resolution hyperspectral analysis of 'ordinary' light
- now applying SHS in combustion

Generic Spectroscopy Arrangements









- the selected arrangements all offer the possibility to engineer the light source rather than (or in addition to) the detector

Why engineer the light source?

(since you could just use a light bulb and a SHS detector)

1. Efficient at high-resolution

- Spectral resolution decoupled from collection etendue. Examples: in fluorescence, collect > 1 Sr from a 1-mm emitter and still maintain < 1 GHz spectral resolution in an excitation scan; likewise in absorption, beamsteering does not compromise spectral resolution

2. Simple, rugged, compact, all-fiber…

- Hyperspectral lasers more readily multiplexed than hyperspectral detectors, e.g. for multi-beam tomography, multi-channel sensors to cover ultra-broad spectral ranges

3. Compatible with simple detectors

- Not paced by camera technology (limited readout rates, usually optimized for visible range, etc.)

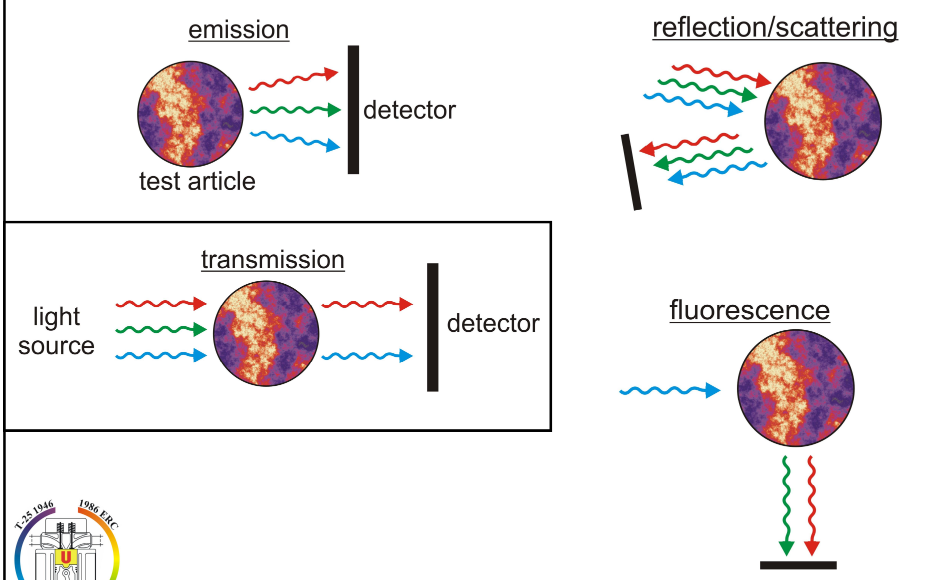
4. Can complement spectrometers

- Ultimately, may want to combine hyperspectral light sources and detectors (e.g., for combined excitation-emission fluorescence spectroscopy)

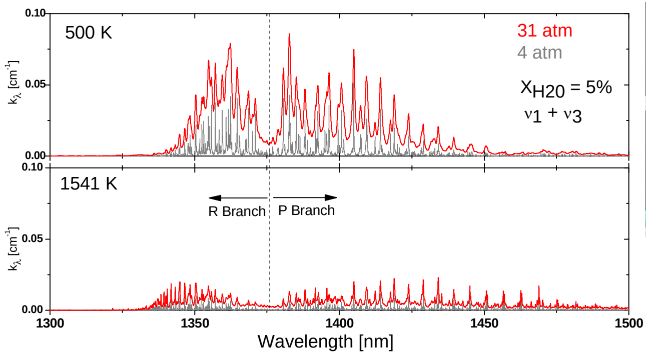
5. Light can be ordered, thus eliminating thermal beating

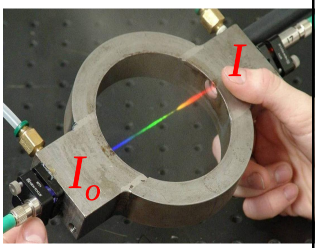
- For 5 μs-duration measurement at 1 cm^{-1} resolution, $noise_{pk\text{-}pk}$ = 1.3%

Generic Spectroscopy Arrangements



Engine Measurements by Absorption Spectroscopy





Beer's Law:

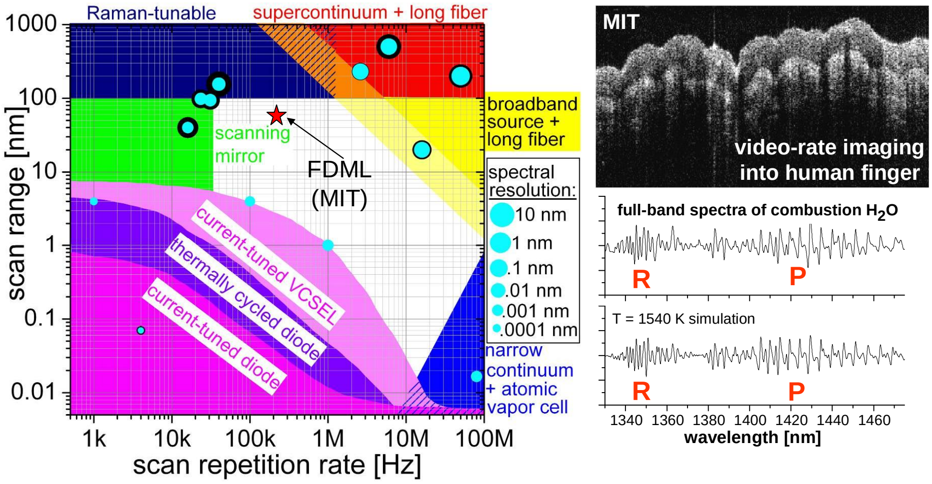
$T_\lambda = (I/I_o) = \exp(-k_\lambda L)$

$k_\lambda = f(T,X,P)$

Line of sight average

- Goal: use absorption spectroscopy to quantify gas temperatures, species mole fractions, and/or pressure, in engines

Laser engineering: wavelength-agile lasers



- Many laser systems developed; resulting sensors allow continuous spectral monitoring in dynamic environments